Sub-20-K Noise Temperature LNA for 67-90 GHz Frequency Band

Pekka Kangaslahti[1], Kieran Cleary[2], Jacob Kooi[1], Lorene Samoska[1], Richard Lai[3], Michael Barsky[3], Xiaobing Mei[3], Stephen Sarkozy[3], and Mikko Varonen[4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA
[2]California Institute of Technology, Pasadena, CA 91109 USA
[3]Northrop Grumman Corporation, Redondo Beach, CA 91109 USA
[4] Aalto University, Espoo, Finland

Abstract— **Indium Phosphide MMIC LNAs are enabling new capabilities in instrument development. The development of arrays of hundreds of cryogenically-cooled millimeter wave receivers has previously been challenging, but is now achievable with highly repeatable MMIC processes and advances in cryogenic on-wafer testing of LNAs. We have developed InP HEMT LNA MMICs for the 67-90 GHz frequency band that is the last missing receiver system from the ALMA. These MMICs provided average performance of less than 22.5 K noise temperature over the frequency band and minimum noise temperature of 17.5 K at 72 GHz. These LNAs achieve NT=220K (NF=2.4dB) at 90 GHz for Earth remote sensing instrument on Sentinel-6. Our HRMR (High Resolution Microwave Radiometer) achieves NEDT < 0.05K enabling Sentinel-6 to measure coastal ocean topography at 3 km resolution with better than 1 cm accuracy.**

Index Terms— **MMIC, LNA, InP, ALMA, cryogenic, ocean topography, Sentinel-6**

I. Introduction

Receiver arrays are attractive for enhancing the sensitivity of a radiometer by scanning multiple pixels simultaneously, or for synthesizing large apertures by using interferometry. These receiver arrays are easiest to build using MMICs due to the repeatability of the circuits and the ability to prescreen the MMICs before assembly. The largest astronomical instrument in operation is the Atacama Large Millimeter and submillimeter Array (ALMA) in northern Chile at an elevation of 5 km. ALMA consists of 54 12-meter antennas and 12 7-meter antennas; each antenna system includes a cryostat with space for receiver cartridges in ten different bands. The only remaining receiver system that was not yet installed or in production is band 2 covering 67 to 90 GHz in two polarizations.

Recent advances in InP technology have resulted in amplifiers with minimum noise temperatures in the 22 to 34 K range in this frequency range [1]-[4]. We designed InP MMICs in 35 nm gate length technology for this frequency band. These LNAs achieved 17.5 K noise temperature at 72 GHz and an average of 22.5 K of noise temperature over the full frequency band. These are the lowest noise temperatures reported at this frequency band for a cryogenically cooled packaged amplifier.

The InP technology is well suited for both cryogenically cooled and room temperature operation. We applied these LNAs for 90 GHz receivers on Sentinel-6 ocean topography mission. Sentinel-6 carries a radar altimeter to provide high precision and timely observations of the topography of the global ocean. This information is essential for the continued monitoring of changes in sea level, and for operational oceanography. The path delay of the radar altimeter signal varies depending on the quantity of water vapor in the atmosphere. To achieve under one centimeter accuracy in the ocean topography measurement the water vapor is characterized with microwave radiometers. For extending this calibration within a few kilometers of the coast our HRMR instrument uses millimeter wave frequency receivers to improve the spatial resolution of the water vapor measurement with the available one meter antenna aperture [5]. These 35nm LNAs provide the required low noise for direct detection radiometers that operate with low power and fit in the low volume available on the focal plane of the reflector.

II. Designs of LNAs

Indium Phosphide HEMT technology has advanced from 100 nm technology to under 35 nm gate lengths [4],[6],[7]. As expected, with the reduction in gate length, the transconductance of our devices improved from close to 1000 mS/mm to 2300 mS/mm and beyond. The gate capacitance was also reduced and this led to high F_t of above 400 GHz. Further improvements in contact resistances and transistor design reduced the noise of the device. A significant factor for producing low noise amplifiers is the sharp turn-on of these devices that leads to high transconductance at the low bias currents that are required for low noise performance. With these optimum device characteristics available in our InP technology, the remaining task is to decide on the number of fingers and finger width of the device to use in the design of the low noise amplifier. At W-band we demonstrated that a four finger device with 15 um fingers would be optimum for a cryogenic LNA [8].

A. Implementation of LNA Design

After the selection of device size a few different LNA design topologies were used for the final low noise amplifiers to achieve variation in the processed LNAs. Both three-stage and two-stage common-source designs were implemented with microstrip matching circuits on the 2-mil thick substrate. Standard MIM thin-film capacitor and TaN resistor processes

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were available to design the bias circuits on the LNA MMIC. Fig. 1 and Fig. 2 show photos of the designed MMICs.

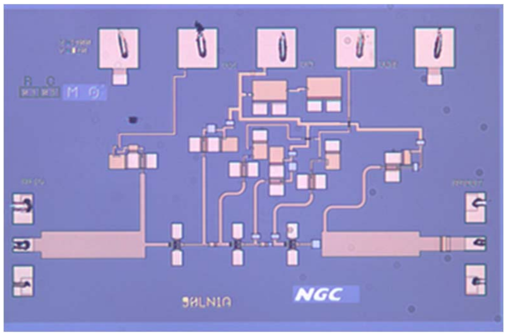

Fig. 1. A three-stage common-source design. The size of the MMIC is 1300 um x 820 um.

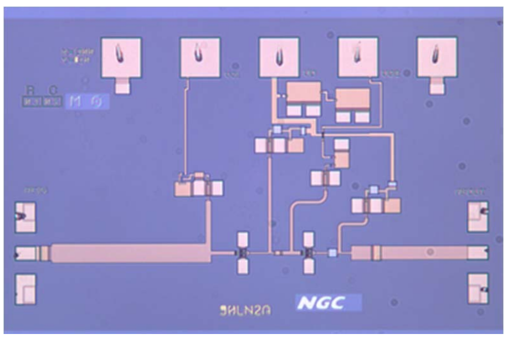

Fig. 2. A two-stage common-source design. The size of the MMIC is 1300 um x 820 um.

B. LNA Processing

The processing of the layouts included four three-inch wafers, two each of 75% and 100% Indium content in the device channels. The 75% channel results in slightly lower maximum transconductance, and provides a variation in the transistor performance which can improve the likelihood of success for the LNA design. The wafers contained several different designs of various operating frequencies, so the quantities of chips per design were 25-90 per wafer. The four wafers were tested at room temperature after thinning the wafers to 50um and then the wafers were diced for cryogenic testing. The on-wafer yield was in the 85-90% range.

III. LNA TESTING

The on-wafer testing of LNAs allowed us to pick the amplifier chips that functioned well at room temperature. However, we have not been able to predict which of the LNAs achieve best cryogenic noise performance based on this room temperature data. We demonstrated that with a purpose built cryogenic test station the diced MMICs can be screened for low noise performance [9],[10]. Fig. 3. shows cryogenic test data for on-chip testing of our two-stage LNA MMICs and Fig. 4 includes the data for the three-stage LNA. The probe station provides a relative, not absolute, measurement due to uncertainties in the temperature of the lossy part of the input probe. However, a relative measurement allows for selection of best performing chips and designs. This is highly valuable for cryogenic array development as the best cryogenic LNAs can be selected for use as the first amplifiers in the receiver.

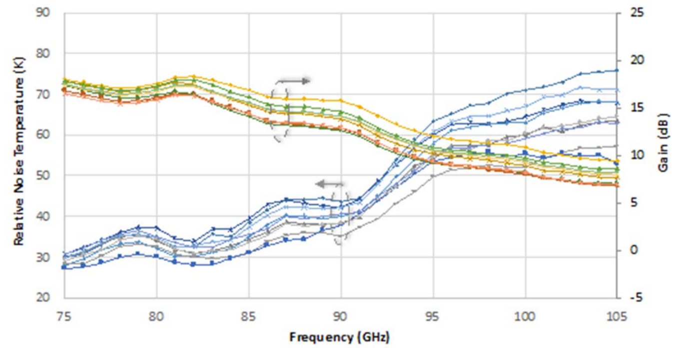

Fig. 3. Gain and relative noise temperature of screened 2-stage LNA MMICs. These on-chip measured data are for nine different chips of the same two-stage design in Fig. 2. All chips show good performance, but the best ones can be selected for first stages of the cryogenic receivers.

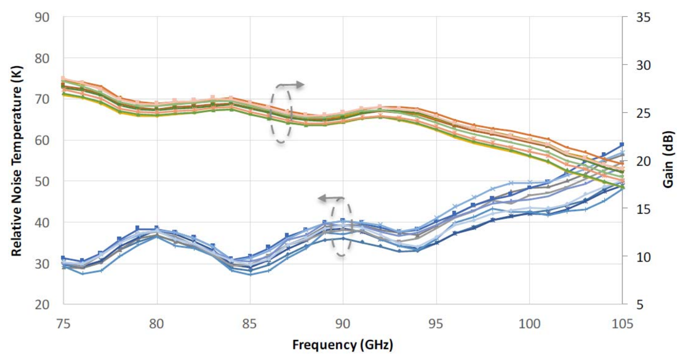

Fig. 4. Gain and relative noise temperature of 3-stage LNA MMICs

We picked the screened lowest-noise amplifiers for packaging in split-block brass housings with thin-film microstrip to waveguide transitions (Fig. 5). These housings had WR-10 waveguides that have cut-off at 58 GHz and normal operating range from 75-110 GHz. This may degrade the presented result at the lower end of the frequency band.

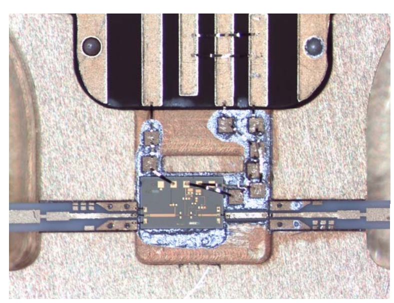

Fig. 5. Waveguide housing with assembled MMIC and thin-film probes to waveguides. Bias is provided with a PCB that includes capacitors and resistors for bias stabilization of the amplifier.

The amplifiers were cooled to under 20 K ambient temperature, and noise temperature and gain characterized with hot/cold Y-factor tests. An isolator and second LNA were used in the cryostat to reduce the back-end contribution in the measurements. The back-end also included a room temperature WR-10 second harmonic mixer that contributed to the gain ripple at the low end of the frequency band. The test results in Fig. 6 demonstrate the flat, slightly above 20K average noise temperature of the LNA over the full 67-90 GHz frequency band and some frequency points where the noise temperature is less than 20 K. These results are the lowest reported and indicate over 10K improvement in the average noise temperature compared to the MIC amplifiers designed for the same band [11]. The optimum bias for lowest noise was about a factor of three to four lower in cryogenic testing at 20 K than at room temperature. The reduction in minimum noise temperature was a factor of seven to ten from room temperature to 20 K ambient. The amplifier was biased to Id=5mA total current for the two stages, which corresponds to 42 mA/mm current density on the transistors.

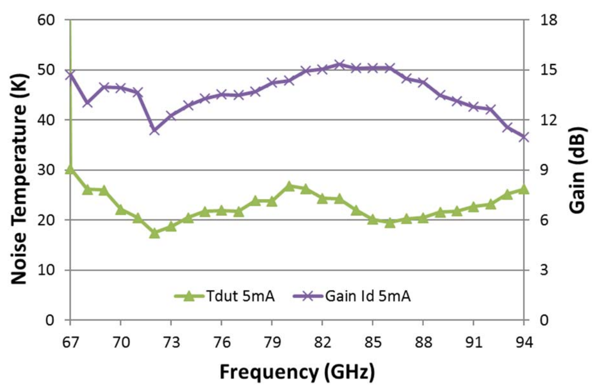

Fig. 6. Measured gain and noise temperature of the packaged 2-stage LNA at 20K ambient temperature. The LNA was biased to 5 mA of current that corresponds to 42 mA/mm of current density.

The results for 3-stage amplifier are shown in Fig. 7. It had minimum noise temperature of 29 K and average noise temperature of 34 K over the frequency band. The gain of the amplifier is 25 dB, so it is suitable for use as the second stage for an amplifier module, or as the only amplifier in front of a mixer. These results were achieved with a total drain current of 10 mA and voltage of 0.87V. If the drain current is increased to 15 mA, the noise temperature increases by 3K and gain will increase by 1.5 dB. These current values correspond to 56 mA/mm and 83 mA/mm current densities on the transistors.

Room temperature data for the two-stage and three-stage amplifiers are in Fig. 8. and Fig. 9. As was discussed previously, the drain current of the transistors needs to be increased for optimum room temperature operation. At room temperature the three stage design had a noise temperature of 220 K (NF=2.4dB) and G=23dB of gain. These results were achieved at drain current of I_d=30mA, corresponding to current density of 167mA/mm on the transistors.

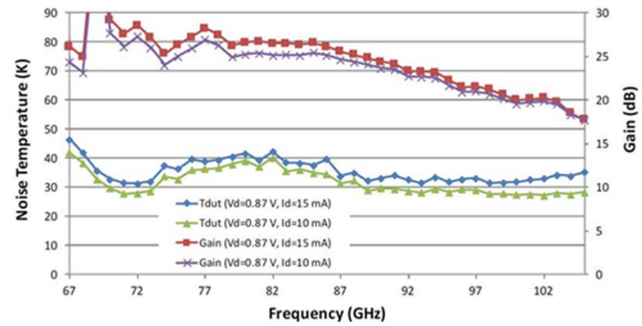

Fig. 7. Measured gain and noise temperature of packaged 3-stage LNA at 20K ambient temperature. With total current of 10 mA the minimum noise temperature of the LNA is 29 K.

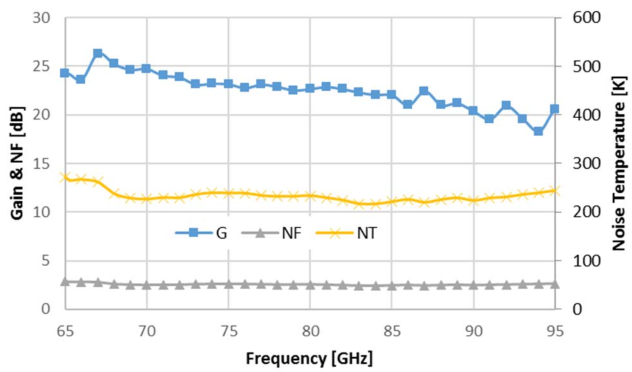

Fig. 8. Room temperature data for the three-stage LNA. The LNA is biased to Vd=1.1V and Id=30mA. Minimum noise figure is about 2.4 dB and noise temperature 220K.

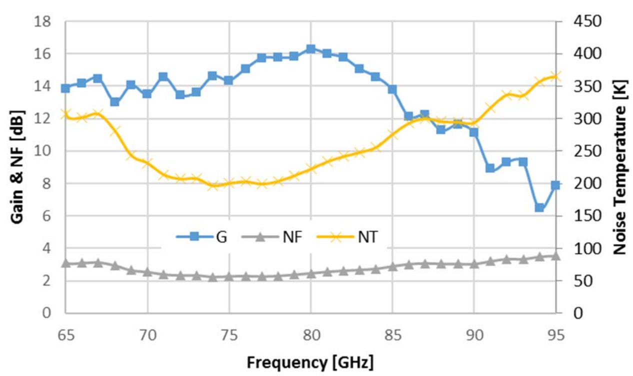

Fig. 9. Room temperature data for the two-stage LNA. The LNA is biased to Vd=1.1V and Id=20mA which corresponds to 167 mA/mm current density. Noise temperature is 200 K and noise figure is 2.3 dB

The two-stage amplifier results in Fig. 9. were measured at the same current density of 167mA/mm. The drain current was Id=20mA and the drain voltage Vd=1.1V when the gain was 12..16 dB across the frequency band and NT=200K at minimum point (NF=2.3dB). The lower gain of the two-stage amplifier may have caused increase in the room temperature noise because of the losses in the microstrip lines in the housing at the output side of the amplifier (see Fig. 5.).

IV. Sentinel-6 HRMR

These LNAs will provide low noise for the HRMR on Sentinel-6 [5] that is not cryogenically cooled. The HRMR has internal calibration and stabilization with noise diodes and Dicke-switch. Even with the added losses from these circuits the receivers achieve NT=700K. With BW=10GHz the expected sensitivity is $\Delta T/T$=2e-5 (assuming 50% of the integration time is used for Dicke-switch reference load measurement and integration time is τ=1 s). Sentinel-6 has an orbit speed of 7 km/s, so in practice there radiometers will only be able to integrate for τ=0.25 s. Thus the expected ΔT= 0.03K, well below the specified 0.2 K. At longer integration times the 1/f-noise of the amplifiers will restrict the improvement in sensitivity because of the non-gaussian nature of the 1/f-noise. The Dicke-switching will remove this effect by allowing comparison to stable reference at a rate that is faster than the 1/f-noise effects. Fig. 10. shows the normalized spectral density of the HRMR 90 GHz receiver output when it is not Dicke-switched. The required Dicke-switch rate is 100 Hz or higher, because at that frequency the spectral density of 1/f noise will be equal to white noise normalized spectral density of 1e-5 V/V/Hz for this radiometer with BW=10 GHz.

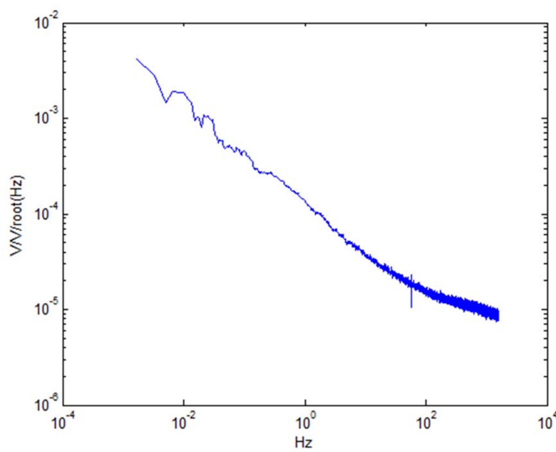

Fig. 10. Normalized spectral density at the output of the HRMR receiver. The 1/f noise is at 2e-4 level at 1 Hz and reduces to below white noise level at above 100 Hz.

V. Conclusion

This LNA development has demonstrated state-of-the-art results from the design of 67-90 GHz LNAs with a high yield InP LNA process. Diced MMICs were screened in a cryogenic probe station before selecting the best performing LNAs. This technique yields excellent results for receiver arrays where hundreds of cryogenic receivers have to be built with a reasonable cost. The lowest noise MMIC LNAs can be preselected and populated as the first stages in the receiver modules. The developed LNAs enable low noise amplification for HRMR instrument on Sentinel-6. With faster than 100 Hz Dicke-switching rate the receivers will provide ΔT= 0.03K sensitivity.

Acknowledgment

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